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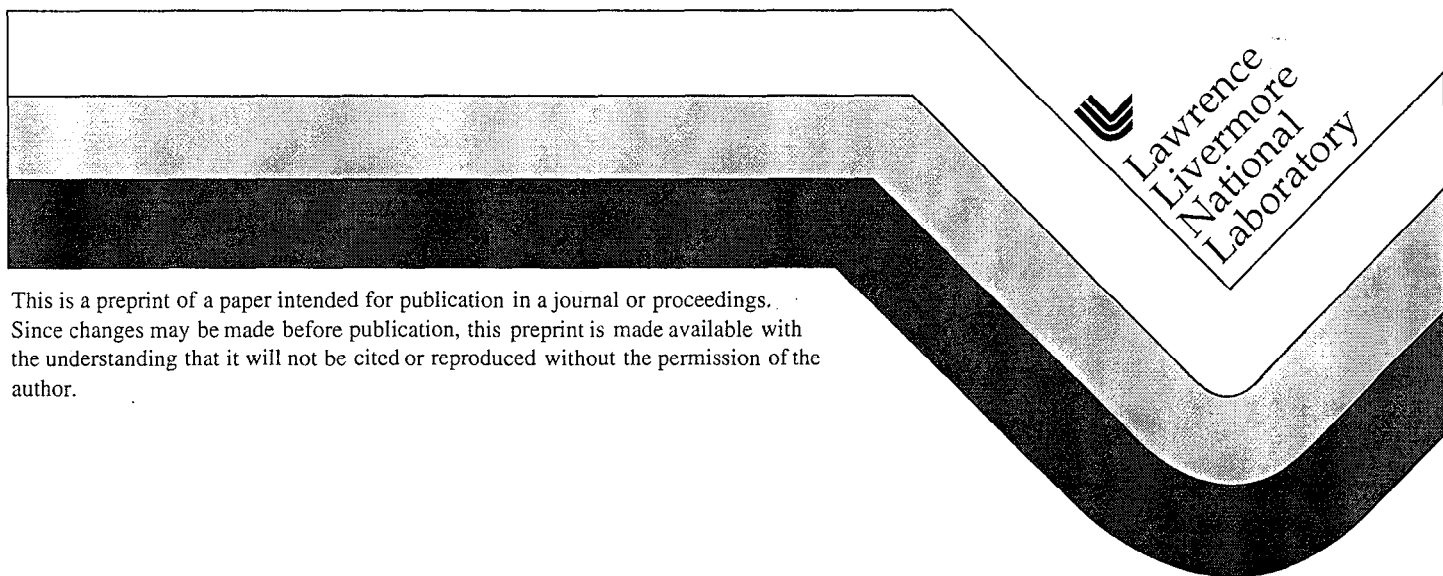
PREPRINT

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J. Dunn, A. L. Osterheld, V. N. Shlyaptsev, Y. Li, J. Nilsen,  
R. Shepherd, L. B. Da Silva

This paper was prepared for submittal to the  
6th International Conference on X-ray Lasers  
Kyoto, Japan  
August 31-September 4, 1998

February 7, 1999



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# Progress in table-top transient collisional excitation x-ray lasers at LLNL

James Dunn, Albert L. Osterheld, Vyacheslav N. Shlyaptsev <sup>1</sup>,  
Yuelin Li <sup>2</sup>, Joseph Nilsen, Ronnie Shepherd, and Luiz B. Da Silva

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

<sup>1</sup>Dept. of Applied Science, University of California Davis-Livermore, Livermore, CA 94550, USA

<sup>2</sup>ILSA, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

**Abstract.** We present progress in experiments for high efficiency Ne-like and Ni-like ion x-ray lasers using the transient collisional excitation scheme. Experimental results have been obtained on the COMET 15 TW table-top laser system at the Lawrence Livermore National Laboratory (LLNL). The plasma formation, ionization and collisional excitation of the x-ray laser have been optimized using two sequential laser pulses of 600 ps and 1 ps duration with an optional pre-pulse. We have observed high gains up to  $55 \text{ cm}^{-1}$  in Ne-like and Ni-like ion schemes for various atomic numbers. We report strong output for the  $4d - 4p$  line in lower Z Ni-like ion sequence for Mo to Y, lasing from  $\sim 190 \text{ \AA}$  to  $240 \text{ \AA}$ , by pumping with less than 5 J energy on target.

## 1. Introduction

Transient collisional excitation (TCE) was first proposed about a decade ago as a method of achieving high gain and high efficiency in Ne-like and Ni-like ion x-ray lasers [1]. One way of realizing this scheme was to utilize a two-stage laser irradiation process of a nanosecond pulse followed by a high intensity chirped pulse amplification (CPA) picosecond pulse [2]. The long pulse formed the plasma to create the correct ionization conditions and was allowed to expand and cool. The short pulse at  $10^{15} \text{ W cm}^{-2}$  then rapidly heated the electron temperature to  $\sim 1 \text{ keV}$  thus generating a transient population inversion in the  $n = 3$  excited states by strong monopole collisional pumping from the ground state. It was predicted that the high transient gain could last for timescales from femtoseconds up to tens of picoseconds but would rapidly terminate as a result of collisional redistribution of the electron population among all excited levels and plasma overionization. In special cases, lasing at significantly lower gains could still continue by quasi-steady state excitation later in time while the electron temperature remained sufficiently high to pump the upper levels.

This scheme was successfully demonstrated recently for Ne-like Ti lasing on the  $3p \rightarrow 3s$  transition at  $326 \text{ \AA}$  at the Max Born Institute, Germany [3]. A few joules of laser energy in each beam was sufficient to generate high small signal gain of  $19 \text{ cm}^{-1}$ . It was extended to the Ni-like ion  $4d \rightarrow 4p \ J = 0 \rightarrow 1$  transition at  $147 \text{ \AA}$  for Pd [4, 5] at the Lawrence Livermore National Laboratory (LLNL) where high gains of  $\sim 35 \text{ cm}^{-1}$  and a gain length product of 12.5 were reported. Gain saturation in Ne-like Ge [6] and Ti [7] have been achieved with higher

energies on target using the VULCAN-CPA laser at the Rutherford Appleton Laboratory (RAL), UK. The scheme has also been successfully extended to many other Ne-like and Ni-like ions for experiments performed at various laboratories [8]. Perhaps the most notable aspect of the TCE scheme is not only the high efficiency and high observed gain but also the reduction of the laser drive energy to generate the inversion. This has allowed the scheme to be explored by small CPA picosecond lasers.

There have been several notable *collisional* x-ray lasers reported recently which use small table-top pump sources. These have included fast capillary discharge schemes which have demonstrated gain saturation and several tens of microjoules output for Ne-like Ar lasing on the  $3p \rightarrow 3s$  transition at 469 Å [9]. Also, the Pd-like Xe scheme was demonstrated where an inversion on the  $5f \rightarrow 5d$  transition at 418 Å was produced by a 40 fs laser pulse [10]. These collisional excitation x-ray laser schemes have also been demonstrated at high repetition rates.

Recent experimental results are reported for research on the TCE scheme at LLNL using the COMET laser. Strong lasing has been demonstrated on low Z Ni-like ions  $4d \rightarrow 4p$  schemes at around 200 Å and high small-signal gains in excess of 50 cm<sup>-1</sup> are determined for lasing on the Ne-like V  $3p \rightarrow 3s$  lasing line at 304.5 Å.

## 2. Experimental Description - the COMET Laser Facility

The initial experiments on the transient gain Ni-like Pd x-ray laser [4, 5] were performed using the LLNL JANUS laser facilities in June and July of 1997. In those studies, an 800 ps duration, 5 J energy rod shot from JANUS provided the long pulse plasma forming beam while the JANUS 500 fs laser produced the short excitation pulse. In early 1998, the short pulse laser was re-built with a

Parameter	
Long Pulse (1053 nm)	600 ps (FWHM), 15 J EOT
Short Pulse (1053 nm)	500 fs - 10 ps (FWHM), 7.5 J EOT
Peak Power	15 TW (7.5 J EOT in 500 fs)
Optional pre-pulse	6% of main pulse, 2 ns early
Beam Diameter	8.4 cm
Line Focus	25 - 100 µm × 12.5 mm (W × L)
Laser Shot Rate	1 shot/4 minutes

Table 1. COMET Laser Driver and Shot Parameters

further amplification arm to deliver multiple pulse beams on target. Thus, the Compact Multipulse Terawatt (COMET) laser was established as an independent system to explore the transient gain x-ray laser scheme. This facility is adjacent to the JANUS laser with options for combined high energy beams in future experiments.

The COMET laser can simultaneously deliver on target a pre-pulse beam, a long 600 ps pulse and a high power 15 TW short pulse. Maximum available energies on target in the long and short pulses are 15 J and 7.5 J, respectively and these energies can be adjusted independently (as summarized in Table 1, right). The laser occupies two standard optical tables of dimensions 1.2 m × 3.6 m with a total area less than 10 m<sup>2</sup> and so is in the table-top class. This system is a hybrid chirped pulse amplification laser consisting of a Ti:sapphire oscillator and regenerative amplifier tuned to 1053 nm and 4-stage Nd:phosphate glass power amplifiers. The laser layout is shown in the rendering in Figure 1. On the first table, the 100 fs oscillator pulse is chirped to 1 ns in a folded single grating stretcher and injected into the regenerative amplifier operating at 10 Hz. A single pulse is switched out after amplification to the millijoule level and is passed through two sequential pulse slicers consisting of a double glan polarizer/Pockel cell combination. This reduces the low intensity leading and trailing

pulses at the 9 ns regen cavity interval to less than  $10^{-9}$  of the main pulse intensity. The pulse is amplified in a 7 mm rod and relayed to the second table where it is amplified to several joules in the 16 mm and 25 mm diameter rod amplifiers. The beam is split to form two paths which are then double-passed in two final 50 mm diameter amplifiers. The final beam diameter is 8.4 cm diameter. One arm is compressed in a vacuum grating compressor box to generate a short pulse of 500 fs (FWHM). The long pulse arm with a duration of 600 ps (FWHM) remains stretched and is sent through a delay line: this can be adjusted to vary the arrival of the

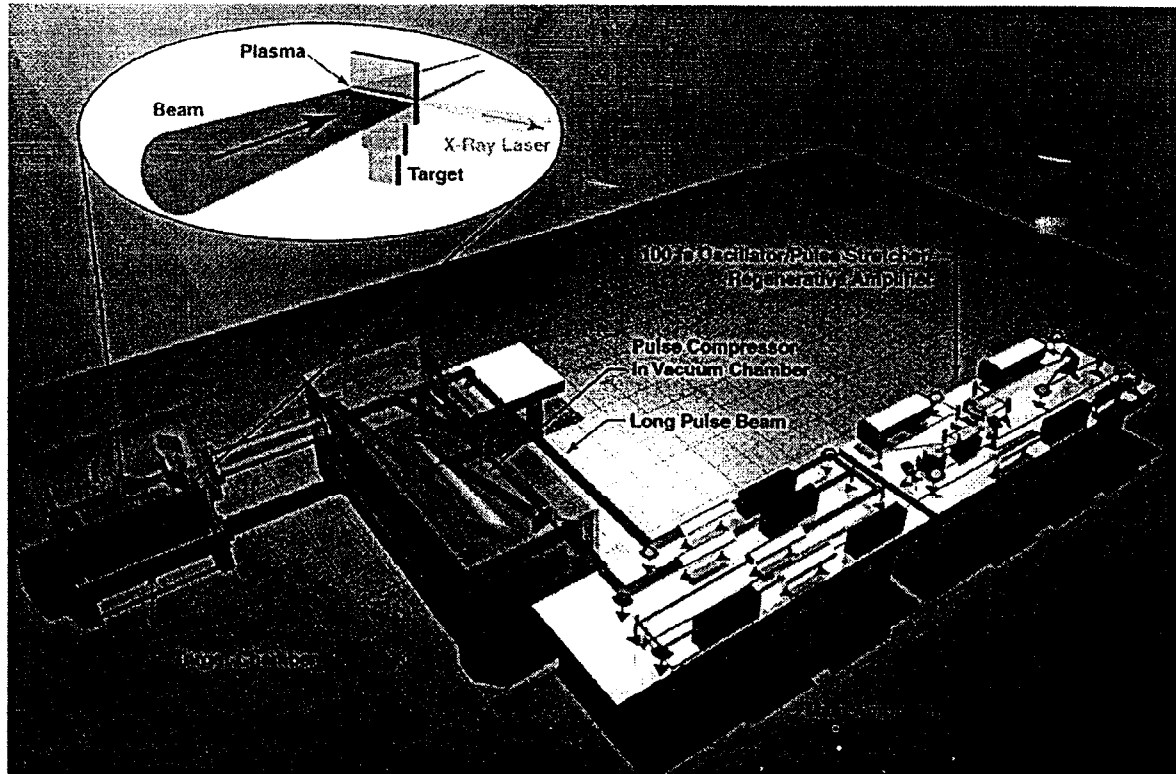


Figure 1 Rendering of the Compact Multipulse Terawatt (COMET) laser at LLNL. The laser occupies two standard optical tables of dimensions 1.2 m  $\times$  3.6 m.

short pulse beam from between 0 to 3 ns after the peak of the long pulse beam. This allows a jitter-free synchronization of the two pulses. The short pulse is typically lengthened to  $\sim 1$  ps by detuning the compressor. The two beams are co-aligned and propagated under vacuum to the target chamber where they are focused to a  $75 \mu\text{m} \times 12.5 \text{ mm}$  line focus using a cylindrical lens and a paraboloid combination. The laser can be fired once every 4 minutes and is limited by the cool-down time of the amplifiers. A typical experimental day will achieve more than 50 laser shots on target. A diagnostic station (not shown) monitors the laser parameters including energy, long and short pulse duration, pulse separation, near field image, focal spot and spectrum on every shot. In addition, optics (not shown) for generating a controlled pre-pulse can be introduced to generate a pre-formed plasma before the arrival of the long pulse.

The inset diagram in Fig. 1 shows the line focus incident on the stepped targets used to determine the small signal gain of the x-ray laser. The x-ray laser beam is emitted perpendicular to the heating beams (along the axis of the line focus) and is measured using a flat-field variable-spacing grating spectrometer with a back-thinned CCD detector. This instrument covers the wavelength range from 135 to 350 Å in first diffraction order and has a resolving power of  $\lambda/\Delta\lambda = 250$ . In addition a CCD x-ray slit camera with 25  $\mu\text{m}$  spatial resolution monitors the uniformity of the keV x-ray emission from the line focus.

### 3. High Gain Ne-like Ion X-ray Lasers

The first experiments with the COMET laser facility were performed using Ti and V targets in order to drive inversions on the Ne-like ion  $3p \rightarrow 3s$   $J = 0 \rightarrow 1$  transitions at 326 Å and 304.5 Å, respectively. Slab targets up to 1 cm in length were irradiated with  $\sim 5$  J in a 600 ps (FWHM) plasma forming pulse and  $\sim 5$  J in a 1.1 ps (FWHM) excitation pulse. Both materials lased strongly giving similar outputs when the arrival of the short pulse was delayed by 1.5 ns *peak-to-peak* relative to the long pulse. This is in agreement with our previous results for Ti using the JANUS long pulse [11].

There have been other laser-produced plasma experiments showing Ne-like V lasing. An experiment conducted at the Max Plank Institute on the Asterix IV iodine laser reported a stronger short wavelength  $3p \rightarrow 3s$   $J = 0 \rightarrow 1$  transition at 263 Å in addition to the long wavelength 304.5 Å, see Li *et al* [12]. The prepulse technique was used where a 15% prepulse arrived  $\sim 5$  ns in front of the main laser pulse of 450 ps duration with  $\sim 500$  J total energy on a 2.5 cm V target. The long wavelength vanadium  $J = 0 \rightarrow 1$  line also had reduced intensity. This *anomalous* lasing for vanadium was in contrast to target materials from adjacent atomic numbers irradiated under similar conditions: the short wavelength  $J = 0 \rightarrow 1$  line in the adjacent isoelectronic sequence was orders of magnitude weaker. Recently Nickles *et al.* observed transient gain on the long wavelength  $J = 0 \rightarrow 1$  transition for target lengths up to 5 mm [13]. There was no indication of lasing on the short wavelength line or any other transition.

We performed a detailed study of vanadium to measure the x-ray laser gain characteristics. Flat stepped length targets varying from 1 to 10 mm in increments of 1 mm were irradiated by the two laser pulses. A 2000 Å Al filter was placed in front of the spectrometer to reduce higher order grating reflections overlapping the first order. Figure 2 shows a single-shot spectrum from the on-axis spectrometer for a short 2.9 mm target: strong lasing action on the long wavelength  $3p \rightarrow 3s$  line at 304.5 Å is visible and is many orders of magnitude higher than any other line. The total laser energy irradiating the 2.9 mm long target is only 2.6 J which indicates the reduced energy requirement and high efficiency for the transient collisional excitation scheme. Two weaker lines are observed in the spectrum but are not labeled: the

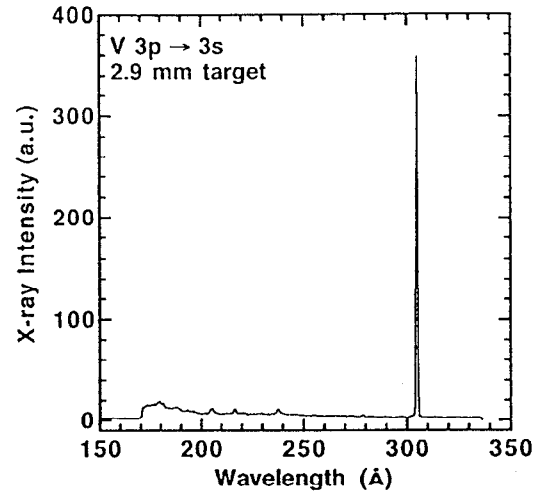


Figure 2 X-ray laser spectrum for 2.9 mm vanadium target irradiated by 5.8 J, 580 ps and 5.5 J, 1.1 ps pulses. Ne-like  $3p \rightarrow 3s$  line at 304.5 Å dominates the spectrum.

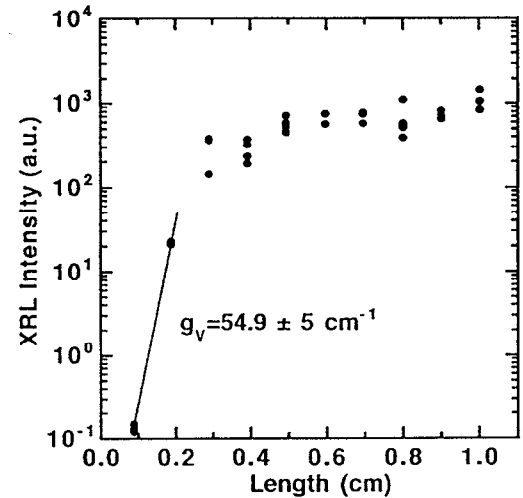


Figure 3 Intensity versus length plot for the Ne-like V  $3p \rightarrow 3s$   $J = 0 \rightarrow 1$  x-ray laser at 304.5 Å. Small-signal gains  $\sim 55$   $\text{cm}^{-1}$  are determined for short target lengths up to 3 mm.

short wavelength  $J = 0 \rightarrow 1$  line is measured at 261.3 Å and is a factor of 500 times less intense compared with the main laser line. There is no *anomalous* lasing for the short wavelength  $J = 0 \rightarrow 1$  line under these transient gain conditions which is in agreement with observed weak lasing of this transition for Ti and Fe targets. The Ne-like V  $3d \rightarrow 3p$   $J = 1 \rightarrow 1$  transition measured at 278.4 Å, just visible in Figure 2, is about 100 times weaker than the main line. Lasing on the  $3d \rightarrow 3p$  line has been observed and predicted for Ti [3, 5, 7, 14] but this is the first time that it has been observed for vanadium or higher atomic number.

Figure 3 shows the intensity *versus* length data for the vanadium 304.5 Å lasing line. Many laser shots, three or more data points per target length, with energy held constant were used on target and excellent reproducibility of the lasing line was observed. The intensity curve can be described as having a region of ultra-high gain for short target lengths below 3 mm rapidly rolling over to lower gain for longer target lengths up to 1 cm. Applying the Linford formula [15] to fit the high gain region, small-signal gains of 55 cm<sup>-1</sup> are inferred from the data with a gain-length product of 12.7 for the 2.9 mm target. The laser output continues to increase at a lower exponential rate with a  $gL \sim 14.6 \pm 0.5$  at 1 cm.

#### 4. Ni-like Ion X-ray Lasers Near 200 Å

Previous experimental work on table-top laser driven collisional schemes was directed at creating population inversions on  $4d \rightarrow 4p$  transitions of low-Z Ni-like ions using three 80 ps pulses separated by 7.5 ns with 1 J per pulse [16]. A line at 189.1 Å from a 5.5 mm Mo slab target was tentatively identified as the lasing line. A follow-up experiment on Ni-like Nb indicated weak lasing with a small-signal gain 2.75 cm<sup>-1</sup> and a  $gL$  product of  $\sim 2$  for the  $4d^1S_0 \rightarrow 4p^1P_1$  line at 204.2 Å [17].

We performed transient collisional excitation x-ray laser experiments on these materials with strong lasing apparent in the spectra of Fig. 4: on-axis single laser shot spectra show the emission from 0.8 cm slab targets of Y, Zr, Nb, and Mo. A 2000 Å Al filter was used in front of the spectrometer for the molybdenum, niobium and zirconium spectra giving rise to the L-edge structure at 170 Å. The strong Ni-like  $4d^1S_0 \rightarrow 4p^1P_1$  x-ray laser transition is clearly visible on each

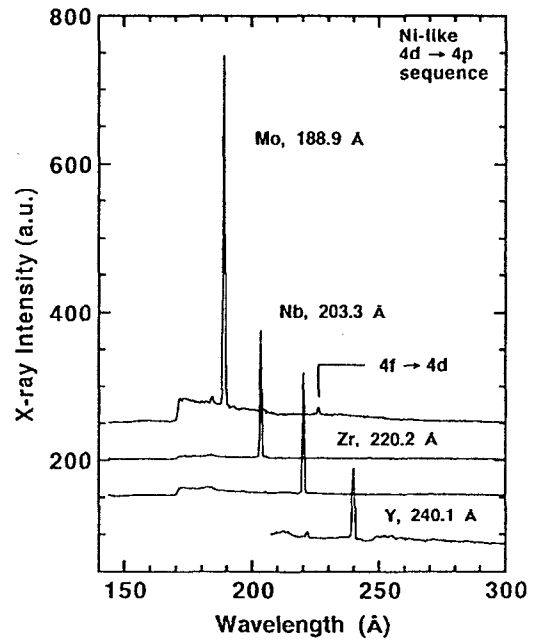


Figure 4 On-axis spectrum of 0.8 cm slab targets of Y, Zr, Nb, and Mo showing the Ni-like  $4d^1S_0 \rightarrow 4p^1P_1$  lasing transition clearly visible on each material. The weaker  $4f^1P_1 \rightarrow 4d^1P_1$  laser transition of Ni-like Mo at 225.9 Å is labeled.

material. Laser driver energies on target were 0.3 J in 600 ps and 4.6 J in 1.1 ps for the yttrium and niobium targets. Slightly higher energies of  $\sim 1$  J in the long pulse and 5 J in the short pulse were used for the zirconium and molybdenum targets, shown here. A limited number of shots were tried on the Y target and so further enhancement of the line intensity should be possible. The wavelengths of the  $4d \rightarrow 4p$  lasing lines were accurately measured (see further details in [18, 19]) and confirmed the identification of the previous experiments [16, 17]. In addition, the  $4f^1P_1 \rightarrow 4d^1P_1$  x-ray laser transition of Ni-like Mo at 225.9 Å was observed and labeled in Fig. 4. This transition is the analogue of the Ne-like  $3d \rightarrow 3p$

transition and is populated by collisional excitation and self-photopumping by the  $4f \rightarrow 3d$  resonance line as described recently by Nilsen [20]. Further experimental details of the low-Z Ni-like lasing are reported in ref. [21].

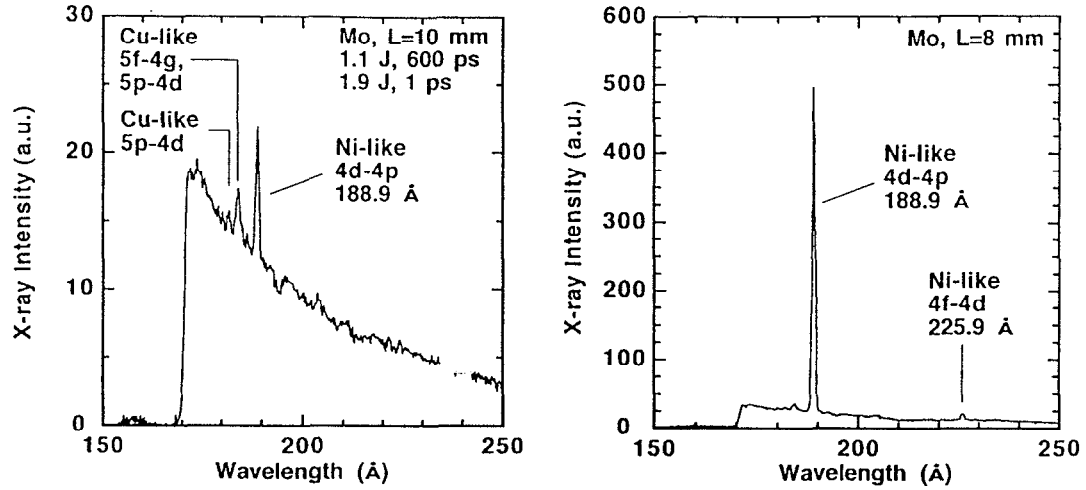


Figure 5 (a) Spectrum (left) for 3 J total energy shows low intensity Mo x-ray laser line. (b) Increasing short pulse laser energy (right) from 1.9 J to 4.9 J, total laser energy now 6 J, substantially increases the output from 8 mm target.

The observed amplification of the lasing lines in this scheme is very sensitive to the transient electron temperature produced by the high irradiance short laser pulse. This is underlined in Fig. 5 which shows two spectra from a Mo target heated by a 1.1 J in a 600 ps pulse but with different 1 ps irradiation conditions. The 12.5 mm line focus remains fixed in both cases. Decreasing the short pulse laser energy to 1.9 J incident on a 10 mm Mo slab substantially reduces the excitation conditions to close to the threshold for pumping the inversion, Fig. 5(a) left spectrum above. However, it is still stronger than the adjacent labeled non-lasing Cu-like ion emission lines. A modest increase to 4.9 J in the 1 ps pulse increases the output by more than 50 times for the 8 mm target in Fig. 5 (b) right. Maintaining the short pulse energy at  $\sim 5$  J on Mo slab targets, an intensity *versus* length scan shows that a small-signal gain of  $21 \pm 2$  cm $^{-1}$  for the  $4d \rightarrow 4p$  transition is inferred up to 4 mm, Fig. 6 (a) left. The overall  $gL$  product is close to 12 for targets up to 10 mm. The gain rolls over smoothly in a similar way observed previously for Pd [4, 22, 23] but not as abruptly when compared to V in Fig. 3. The lower data points in Fig. 6(a) show a constant gain with length for the  $4f \rightarrow 4d$

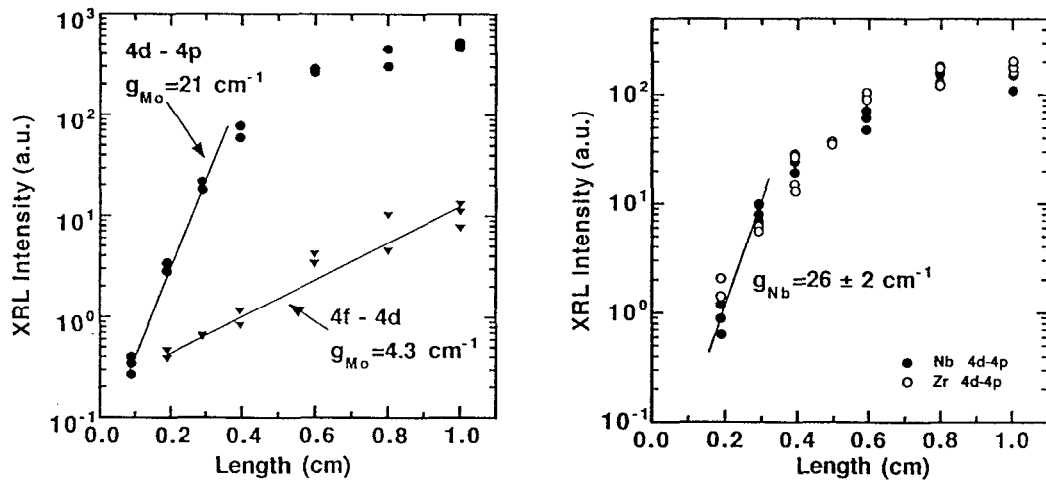


Figure 6 (a) Intensity *versus* length plot (left) for  $4d \rightarrow 4p$  and  $4f \rightarrow 4d$  laser lines of Mo and (b) similar plots for  $4d \rightarrow 4p$  lines of Nb and Zr (right).



transition. Further investigation of this transition in simulations and experiments is required. Repeating the gain measurements for Nb and Zr indicates gains of  $26 \text{ cm}^{-1}$  and  $17 \text{ cm}^{-1}$ , respectively with similar intensity for target lengths of 10 mm. Overall, at 1 cm lengths the Nb and Zr have about  $\sim 2 - 3\times$  lower intensity than the Mo, but otherwise show robust, repeatable output. With such low energies in the driving laser, low Z Ni-like laser lines are very good candidates for tabletop applications requiring bright coherent radiation near  $200 \text{ \AA}$ .

## 5. Discussion and Future Work

Investigation of the Ne-like ion scheme with  $\sim 11 \text{ J}$  of total energy in the  $12.5 \text{ mm}$  line focus has produced strong lasing in the vanadium  $3p \rightarrow 3s \ J = 0 \rightarrow 1$  transition at  $304 \text{ \AA}$ . High small-signal gain of  $55 \text{ cm}^{-1}$  has been inferred for short target lengths up to  $3 \text{ mm}$  where the gain-length product is estimated to be  $\sim 12.7 \pm 0.5$  for a  $2.9 \text{ mm}$  long plasma. The very strong increase in the lasing line abruptly changes to a lower constant gain with excellent shot-to-shot reproducibility. The x-ray laser output above  $3 \text{ mm}$  increases by a further  $5 \sim 6$  times for a  $10 \text{ mm}$  target. This corresponds to  $gL \sim 14.6 \pm 0.5$ . This behavior is very similar to previous results measured for Ti [5] with the exception that the knee in the intensity *versus* length curve occurred at  $5 \text{ mm}$  as a result of the lower gain for Ti. Although the gain measurements were not repeated for Ti at this time, the output of the Ti  $3p \rightarrow 3s$  laser line was similar to the V  $3p \rightarrow 3s$  laser at  $10 \text{ mm}$  lengths. It should be noted that with the observed very high gains for vanadium, the gain-length product discussed here is conservative in order not to misinterpret possible transient gain lifetime effects with gain saturation effects [22]. A small over estimate of the gain by  $10 \%$  would be sufficient to increase the gain-length product into a saturation regime. However, in spite of this we can state with confidence that the Ne-like ion schemes for Fe through Ti are consistently very close to saturation (See Figure 7 for a comparison between the output of Ne-like and Ni-like lasing transitions). Simulations and experiments with traveling wave geometry are under way to improve the output and energy extraction efficiency but also resolve when gain saturation behavior is achieved.

In conclusion, we have presented recent experimental results for transient collisional excitation Ne-like and Ni-like ion schemes using the COMET tabletop laser at LLNL. This extends our previous Ni-like Pd and Ne-like Ti measurements in the ongoing study of high efficiency laser driven x-ray lasers [4, 5]. We have also demonstrated for the first time unequivocal lasing near  $200 \text{ \AA}$  on low-Z Ni-like ions for molybdenum through yttrium targets with a total energy of  $\sim 5 \text{ J}$ , but even with  $3 \text{ J}$ . Gain length products of  $11 \sim 12$  have been observed. Characterization experiments with measurements of the deflection and divergence angles of the x-ray laser beam at the plasma column exit have been started to better understand the continually decaying gain in the intensity *versus* length curve. This opens the way forward for further improvements in the efficiency to produce a sub-joule, laser-driven, high repetition rate collisional x-ray laser below  $200 \text{ \AA}$ .

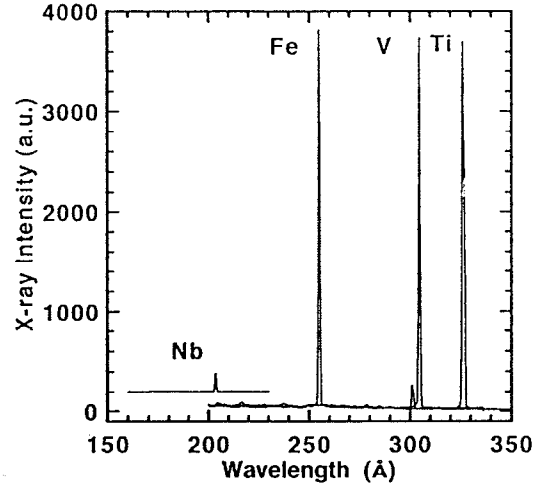


Figure 7. Comparison showing stronger x-ray laser output from Ne-like Ti, V and Fe  $3p \rightarrow 3s$  lasing lines with Ni-like Nb  $4d \rightarrow 4p$  transition for  $0.8 \text{ cm}$  targets. Relative intensities are consistent with a  $gL$  product close to 15 for Ne-like lines.

**Acknowledgements** – The authors would like to thank Mark Eckart and Richard Ward for their continued support of this research. We also thank Jim Hunter and Bart Sellick for technical assistance. V.N.S. and Y.L. acknowledge support from Hector Baldis of the Institute for Laser Science and Applications (ILSA). This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No.W-7405-ENG-48.

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